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PERSISTENCY OF ORGANIC CONTAMINANTS IN GROUNDWATER, LESSONS FROM SOIL POLLUTION INCIDENTS IN THE NETHERLANDS

B.C.J. ZOETEMAN, E. DE GREEF and F.J.J. BRINKMANN
National Institute for Water Supply, Voorburg, The Netherlands

ABSTRACT

Based on an inventory of the presence of halogenated substances in raw water of 232 groundwater pumping stations and on the study of a number of soil pollution incidents in The Netherlands a compilation of more than 100 organic substances identified in contaminated groundwater is discussed. Subsequently the reason why a number of these substances are very persistent under the circumstances prevailing in the soil is analysed. Water solubility is shown to be a major parameter determining the occurrence in groundwater of frequently used chemicals and controlling to a large extend the persistence in groundwater of non-degradable organic chemicals. A list of 12 pollutants, mainly hydrocarbons and chlorinated hydrocarbons, which are of a major concern due to their widespread use, transportability and persistence, observed in groundwater in The Netherlands.

INTRODUCTION

Up till a few years ago groundwater has been regarded in The Netherlands as a water source of outstanding reliability as far as water quality is concerned. It was generally considered to be safe, particularly from a microbiological and toxicological point of view. Recently however, much has changed. The first signs os deterioration of groundwater quality were noticeable many years before. For instance in The Netherlands in certain parts of the central Veluwe area where a decrease in dissolved oxygen content occurred from 8 mg/l till 4 mg/l in the period 1955 - 1965 (Zoeteman, 1975), which was due to intensified agricultural and bio-industrial activities. World wide similar examples of a rapid increase of e.g. the nitrate content of groundwaters have been reported e.g. in United Kingdom and Israel which could ultimately result in local condemnation of this source for the production of drinking water. Another example is a detailed study by Van der Ende (1980) of some wells of the groundwater pumping

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station Guttecoven located in an agricultural area in The Netherlands, which showed once again that drastic changes in salt and nitrate content have taken place during the past decades (Figure 1.)

However, nobody realized that many chemicals of another nature also had affected our precious groundwaters.

Generally, those compounds detected in surface waters like detergents and pesticides, were undetectable in groundwaters. Biodegradation, hydrolysis and adsorption processes were assumed to remove effectively all organic substances introduced into the soil. This hypothesis proved to be wrong when analytical methods for the detection of relatively volatile organics became available. The accidental discovery in 1976 of the presence of trichloroethylene in groundwater resulted in a sudden awareness of this soil pollution problem. Based on the detection of trichloroethylene in drinking water produced by two pumping stations in the province of Utrecht (Soestduinen, Zeist) the Inspector for Environmental Protection requested a national survey of all groundwater pumping stations in The Netherlands.

The results of this survey will be discussed later in more detail. Only few sources appeared to be really contaminated, but the threat of pollution by industrial wastes seemed to be everywhere. Even the rain had to be considered as a possible source of pollution. A further damage to the 'image of realibility' of groundwater occurred the last two years. In 1980 the presence of solvents like toluene and xylenes underneath the houses of 200 families in the village of Lekkerkerk really shocked the public opinion.

The systematic disposal of thousands of chemical waste containers indicated the possible wide-spread presence of similar or even more dangerous chemicals in the underground and the potential risks of contamination of the drinking water if relatively permeable plastic distribution pipes were in contact with contaminated soil. In Lekkerkerk the discovery of penetration of lower alkyl aromatics through the plastic pipes necessitated an emergency supply of bottled water. In 1980 several other cases of serious soil contamination were discovered such as Broek in Waterland where 8000 drums with e.g. chlorinated benzenes were present. Other examples are the detection of a number of drums with aromatic solvents in Oss and about 3000 drums with acid-tar in Nieuw-Beijerland (Haring et al., 1980). It is expected that about 4000 waste disposal sites exist in The Netherlands from which 800 need further investigation.

Just a few months ago another example of direct contamination of the drinking water by soil contamination was identified in the glass house regions in the Westland where methylbromide, a fumigant applied for soil disinfection, was found to penetrate through local plactic water distribution pipes into the drinking water (Van Duijvenbooden et al., 1981). This discovery resulted in an immediate prohibition of the use of methylbromide in those areas where water pipes could be affected.

Consideration of these cases of pollution of soil and groundwater leads to the question whether there is a common factor in all problems. Which type of substances are generally found to cause problems and why are those compounds as persistent in the soil as if it were chloride ions? Which lessons can be derived from the pollution incidents in this country in order to prevent similar problems in the future?

In the context of this paper only organic chemical substances have been considered. Firstly attention will be given to the type and concentration of organic substances which have been detected in the national survey of pumping stations and in a number of case histories. Subsequently the most frequently occurring compounds are considered in more detail with respect to the characteristics which apparently determine their persistency in the subsoil.

NATIONAL INVENTORY OF THE OCCURRENCE OF VOLATILE HALOGENATED COMPOUNDS IN RAW WATER OF 232 GROUNDWATER PUMPING STATIONS

In the period 1976-1978 all 232 groundwater pumping stations in The Netherlands were sampled by the National Institute for Public Health and analysed for the presence of lower halogenated hydrocarbons by the National Institute for Water Supply. In 54 out of the 232 samples of groundwater lower chloroalkanes and -alkenes were detected at levels of 0.1 µg/l or more. This outcome indicated the widespread presence of halogenated compounds in soil and groundwater. A more detailed presentation of the types of compounds detected, and their frequency of occurrence is given in Table 1.

Table 1

Occurrence of lower halogenated hydrocarbons in groundwater of 232 pumping stations in The Netherlands (1976-1978) (Zoeteman et al., 1978)

Compound	Frequency of detection at levels above 0.01 µg/l (% of total)
Bromodichloromethane	1.5
Dibromochloromethane	1.5
Tribromomethane	1.5
Trichloromethane	60
Tetrachloromethane	43
1.1-Dichloroethene	3.5
1.2-Dichloroethane	0.5
1.1.1-Trichloroethane	17
Trichloroethylene	67
Tribromoethylene	0.5
Tetrachloroethylene	19

Table 1 shows that particularly trichloroethylene, trichloromethane, tetrachloromethane and tetrachloroethylene were frequently found at levels above 0.01 µg/l. In some cases the levels were higher than 10 µg/l. In most cases with concentrations higher than 10 µg/l, a typical industrial waste site could be identified as the origin of the contamination. Often small metal plating industries were involved and occasionally specialized chemical plants. Furthermore, it has been postulated that the lower levels of halogenated compounds, as detected at many locations, could originate from air pollution (Hrubec, 1977)(Trouwborst, 1981). Massive quantities of volatile halogenated compounds are released into the atmosphere which could theoretically result in concentrations of e.g. trichloroethylene in rainwater of about 100 µg/l. In The Netherlands however, levels in rainwater of substances like chloroform and trichloroethylene generally are not above 1 µg/l (Brinkmann, Slingerland, 1981). On the other hand such low levels can still explain the widespread occurrence of these volatile chemicals at concentrations of 0.01 - 0.1 µg/l in the groundwater. Higher levels in groundwater were always found to be associated with local waste dumping.

COMPILATION OF COMPOUNDS DETECTED IN CONTAMINATED GROUNDWATERS IN THE NETHERLANDS

In the preceeding paragraph a limited range of substances has been described. These compounds are involved in groundwater contamination in general and in specific cases of chemical waste dumps. A more general classification of the type of incidents and the kind of compounds involved is given below:

- Waste dumps of chemical industry and of painting and printing industry containing aromatic solvents like toluene, xylene, ethylbenzene and higher alkylbenzenes.
- Waste dumps of chemical industry, metal plating industry and dry-cleaning establishments containing lower halogenated solvents like trichlorethylene and tetrachloroethylene.
- Waste dumps of oil refineries with oil and petrol constituents and production residues.
- Location of former gas works containing cyanides and aromatic hydrocarbons like benzene and napthalene.
- Waste dumps of pesticide manufactures and other non-volatile halogenated compounds.

Main examples are Lekkerkerk (Brinkmann, 1981), Wierden (Van Esch, 1980), Afvalverwerking Rijnmond (Morra, Brinkmann, Piet, 1980), Vlaardingen (Morra, 1980) and Uithoorn (Morra et al., 1981). The data collected in the study of these cases are included in this compilation. Additional data exist in relation to a detailed study of the presence of organic chemicals in the neighbourhood of domestic waste tips in Noordwijk (Morra c.s., 1979), (Piet and Morra, 1980) and Delden (Morra and Piet, 1980) as well as a case-study of groundwater contamination at Rhenen (Morra, 1978).

Based on all this information a compilation of compounds detected in contaminated groundwater in The Netherlands has been made. The result of this exercise is given in Appendix 1.

It is important to note that some compounds have been found only once while others like alkylbenzenes and trichloroethylenes are found frequently. Camphor and fenchone are typically associated with domestic landfills.

FACTORS DETERMINING THE PERSISTENCY OF ORGANIC SUBSTANCES IN THE GROUNDWATER

Water solubility and adsorption behaviour

Chemical contaminants should preferably not be introduced into the soil and should once introduced disappear from the soil groundwater system as soon as possible. Where soil pollution is unavoidable it seems to be of primary importance that substances are transported as little as possible through the soil. In this case the contamination remains local and local measures will be sufficient to remove the contamination later. In the case of soluable pollutants the contamination will be spread over a large area. The latter means that attention should particularly be given to the transportability of substances by movement of the water phase. Substances which can be easily transported and which remain present in the groundwater over a long period of time, should obtain a first priority in measures to remove them from contaminated sites or to prevent their introduction into the soil.

Therefore, in the context of this paper the concept of persistency is discussed in relation to the waterphase in the soil alone and not so much in relation to the combined solid-liquid system. Water solubility of a compound is the first prerequisite for a substance to become a potentially persistent and transportable compound in groundwater. Moreover, water insolubility and the tendency to adsorb on the solid phase of soil are phenomena which have been shown to be closely related, particularly in soils with a high organic matter content. This relationship can be illustrated as discussed below. The Freundlich isotherm for a solid-liquid interface described the relation between the amount of adsorbed substance and the concentration of the substance in the equilibrium solution as follows:

$$C_s = K_s . C_w^n \qquad (1)$$

C_s is the equilibrium concentration retained on the solid phase by adsorption and C_w is the concentration of the compound dissolved in the water. In this empirical equation, n is a constant which generally varies between 0.7 and 1 and K_s may be regarded as the soil-water partition coefficient.

Recently is has been shown (Karickoff et al., 1978) that for the adsorption of a number of lipophylic compounds in soil K_s is related to the octanol-water partion coefficient (K_{ow}). Values of K_s for a single chemical vary with the composition of the soil. As the organic content of the soil affects the K_s value, K_s may be expressed as:

$$K_s = a . K_{sc} \qquad (2)$$

in which a is the fraction of organic matter in the solid phase and K_{sc} is the corrected 'sorption constant', which now is more a real constant for a specific chemical. As stated by Chiou (1977) and Mill (1980) the water solubility (S) as well as K_{sc} are closely related to the octanol-water partition coefficient K_{ow}, which is illustrated by the following equations:

$$\log S = -n \log K_{ow} + c \qquad (3)$$

and

$$\log K_{sc} = a \log K_{ow} + b \qquad (4)$$

According to Smith and Bomberger (1980) equations (3) and (4) can be combined to the more precise equation (5):

$$\log K_{sc} = -0.782 \log S - 0.27 \qquad (5)$$

This equation expresses the sorption behaviour of a chemical in a soil-water system as a function of its (in)solubility in water.

Volatility

It is often not realized that the volatility of a substance does not affect its concentration anymore once a substance has reached the groundwater table. This confusion has lead to 'remarkable' predictions on the distribution of chemicals in the various compartments of the ecosystem which presume evaporation to take place even from the groundwater. An example in this respect gives Table 2, taken from Brock Neely (1980) who predicts the distribution of substances based on a model which neglects the groundwater phase.

Table 2

Estimated distribution of chemicals in various compartments of a simulated ecosystem (Brock Neely, 1980)

Chemical	Vapour Pressure (mM Hg)	Water Solubility (µg/l)	Water (%)	Soil (%)	Air (%)
Toluene	30	4.7×10^5	1	0	99
Tetrachloroethylene	14	1.5×10^5	1	0	99
p-Dichlorobenzene	1	7.9×10^4	1	0.3	98.7
Trichlorobenzene	0.5	3.0×10^4	1	4	95
Biphenyl	9.7×10^{-3}	7.5×10^3	2	9	89
Pentachlorobiphenyl	7.7×10^{-5}	10	1	33	66
Hexachlorobenzene	1.0×10^{-5}	35	2	31	67
DDT	10^{-7}	1.2	3	47	50

It is obvious that this simplification strongly overestimated the effect of the high vapour pressure of chemicals on their persistence in the soil. Is it not striking that especially chemicals indicated to be mainly air contaminants are found to be the major groundwater contaminants in this country and probably also elsewhere. Therefore volatility seems not to be a major factor determining the persistency of chemicals in groundwater.

Degradability

In surface water chemicals are transformed by diodegradation, chemical oxidation and photolysis. In groundwater light does not penetrate, the pH is rather constant and the oxygen content is generally depleted. Based on these characteristics of the soil environment substances not containing oxygen and with a low hydrolysis constant will have the greatest chance of survival. Hydrocarbons and halogenated hydrocarbons are, therefore, more likely to be persistent in groundwater than alcohols, ethers and esters. Oxygenated compounds which do not follow this hypothesis generally are alkyl-substituted or these do contain halogen atoms in the molecule which results in a much lower degradability. Examples of relatively persistent compounds containing oxygen, which were found in groundwaters, are 1.1-dimethoxyisobutane and bis(2-chloro-isopropyl) ether (Zoeteman, 1980).

General characterization of compounds likely to be persistent in groundwater

Based on the above considerations it is likely that the water solubility of a compound is a major factor controlling its potential persistence in groundwater as in many situations of soil contamination the evaporation of a compound can be neglected. Contaminated groundwater will generally be anaerobic. The dissolved compounds not containing oxygen in the molecule, are most likely to escape biological degradation. Persistent substances in groundwater generally are not really hydrophylic, such as oxygen containing substances, which would make them suitable for biological breakdown, nor very hydrophobic, which would make them to adsorb strongly on the solid phase in the soil. Surprisingly these criteria leave substances, like lower alkylbenzenes and halogenated alkanes, which are generally regarded as easily removable due to their oxidizability or volatility, as the ones with the best capability to create problems in groundwater.

VERIFICATION OF THE ROLE OF WATER SOLUBILITY IN CONTROLLING THE POTENTIAL PERSISTENCE OF CONTAMINANTS IN GROUNDWATER

Solubility and occurrence in groundwater

Suppose that concentrations of substances below 1 microgram/litre are of no health concern and are also safe from an environmental point of view. In this case all substances with a solubility of less than 1 µg/l are not dangerous with respect to ground groundwater contamination. It is of interest to see how many compounds meet this criterion. In Figure 2 those compounds are presented which are listed in Appendix 1 and for which data on the solubility (Verschueren, 1977) and the octanol-water partition coefficient K_{ow} (Hansch, Leo, 1979) were available or could be estimated. Figure 2 shows that except for a substance like benzopyrene all compounds normally found have solubilities in water far above the value of 1 µg/l.

Furthermore, it was of interest to verify to what extent the highest concentrations detected approached the solubility value. As figure 3 shows for the hydrocarbons the highest concentration equals the solubility value for benzopyrene and fluoranthene. However, the concentrations of benzene, toluene and xylenes could theoretically reach much higher values than those registered up till now. Maximum levels of the hydrocarbons frequenlty detected in contaminated groundwater generally are 1-2 orders of magnitude below the saturation concentration. For halogenated hydrocarbons the highest concentrations detected are mostly 2-3 orders of magnitude below the saturation concentration (see Figure 4). As Figure 5 shows the more biodegradable oxygen containing compounds are mostly found at maximum concentrations 3-4 orders of magnitude below the saturation concentration. These data indicate that the degree of contamination already described for hydrocarbons and halogenated hydrocarbons can become even worse as far as the water solubility of these compounds is concerned.

Solubility and adsorption on soil

As discussed above, water solubility is closely related to the sorption behaviour of an organic compound and in this way also to the persistence of compounds difficult to degrade. Formula (5) shows a striking simplicity, but has been mainly derived from water-sediment data. Therefore the question was examinated if this relationship holds for the circumstances prevailing in a contaminated soil environment. Data on the presence of hydrocarbons in two heavily contaminated soils in Lekkerkerk and Uithoorn were compared with the relationship given by formula (5) of Smith and Bomberger (1980). The outcome of this exercise is presented in Figure 6 where also the calculated values for the ratio $C_{water} : C_{soil}$ for two compounds naphthalenes and benzopyrene, are shown. The two values presented were calculated from formula (4) by using the solubility data for both compounds given by May et al. (1978) and the K_{ow} data presented by Zepp (1980). As Figure 6 shows, the ratios found under field conditions show a good correlation with those predicted from the solubility data.

Solubility and persistence in groundwater

Would it not be ideal if not only adsorption behaviour but also persistence in the form of the half life of a compound in groundwater could be predicted in a given geohydrological situation from a simple characteristic such as solubility?

To explore this possibility in more detail it is necessary to obtain half life values for chemicals in groundwater. An estimation of half lifes was derived from detailed analytical data relating to a number of sampling points downstream of the solid waste tip at Noordwijk (Morra et al., 1979). The interpretation of the data is somewhat speculative as the water sampled may not have followed the same streamlines. Furthermore, the flow of leachate underneath the waste dump is rather complex. Dispersion has been estimated from values for conservative water constituents. Finally the composition of the soil is probably not homogeneous which makes that the calculation of the half life is only a rough estimate.

A summary of the relevant data is given in Table 3. In general it is evident from this table that the half lifes of many oxygen containing compounds are about 10 times lower than those of the (halogenated) hydrocarbons. A striking example in this respect is cyclohexanon. Indane is a very stable compound with an estimated half life of

1 year.

Compounds with very long half lifes of many years will generally not be found in groundwater as that type of substances has a strong tendency to adsorb on the solid phase. Based on the data of Table 4, but excluding the oxygen containing substances which are decomposed or even formed in the soil, the relationship between half life and solubility resp. K_{ow} was studied. As Figure 7 shows a relationship between half life and K_{ow} seems indeed to be present for these non-biodegradable compounds.

Table 3

Estimated half lifes of organic chemicals detected in percolate of the waste tip at Noordwijk.

Sampling location code	149-3	149-4	145-11	146-11	Estimated half life (years)*
Depth of sampling point (m)	8	39	33	33	
Travel distance (m)	0	30	100	130	
Estimated travel time (years)	0	1	6	10	
Compound	Concentration (µg/l)				
C_6-C_{10} Alkanes	0.3	<0.01	<0.01	<0.01	<0.01
Benzene	100	30	0.3	1	0.3
Toluene	300	100	0.3	0.3	0.1
m/p-Xylene	300	300	0.3	0.3	0.1
o-Xylene	300	100	0.1	0.1	0.03
Ethylbenzene	300	100	0.3	0.3	0.1
C_3-Benzenes	300	100	1	3	0.1
Indane	10	3	1	1	1
Naphthalene	30	30	0.3	0.3	0.3
Biphenyl	3	0.3	<0.03	<0.03	0.1
C_2-Naphthalene	0.3	0.3	<0.03	<0.03	0.1
Chlorobenzene	3	3	<0.01	<0.01	0.1
Dichlorobenzenes	3	1	0.01	0.03	0.3
Trichlorobenzenes	0.1	<0.01	<0.01	<0.01	0.03
Cresols	10	<0.1	<0.1	<0.1	0.01
Methylcresols	30	30	1	0.3	0.3
Cyclohexanon	30	0.1	0.1	<0.1	0.003
Fenchone	100	100	1	1	0.3
Camphor	1000	100	10	3	0.1
Acetophenon	10	<0.1	<0.1	<0.1	0.01
Phenylisocyanate	10	3	<0.1	<0.1	0.1
Butylbenzoate	3	<0.1	<0.1	<0.1	0.01
Tri-isobutylphosphate	10	10	<0.1	<0.1	0.1
Diphenylether	0.1	0.01	<0.01	<0.01	0.03

* Assuming a first order reduction process

Table 4

Compounds of major concern due to their use transportability and persistence observed in the groundwater in The Netherlands

Name	Highest concentration detected (µg/l)	Estimated half life * (years)
Hydrocarbons		
Benzene	100	1
Toluene	300	0.3
Xylenes	600	0.3
Ethylbenzene	300	0.3
C_3 Benzenes	300	0.6
Naphthalenes	30	0.6
Ketones		
Camphor	1000	0.3
Fenchone	100	0.6
Halogenated hydrocarbons		
Dichloromethane	3000	10
Trichloroethylene	1000	2
1.1.1.-Trichloroethane	3000	1
Dichlorobenzene	10	1

* based on adsorption behaviour underneath the Noordwijk waste dump

FINAL CONSIDERATIONS

In our opinion the main lesson to be learned from the numerous cases of 'accidental' soil pollution and continuous groundwater contamination is that often substances are involved which were up till recently considered to be rather harmless and unimportant because of their high volatility, good water solubility and rapid biodegradability under aerobic circumstances. It has been shown in this paper, however, that among the hundred or more compounds regularly found in contaminated groundwater, it are the relatively low molecular and often well-known chemicals which create the greatest problems.

The reason for this striking fact is that volatilization nor oxydative transformation affect chemicals present in anaerobic groundwater. A further lesson from the incidents is that water solubility is a major parameter determining the occurrence in groundwater of frequently used chemicals and controlling to a large extent the persistence in groundwater of the non-degradable contaminants.

Based on these experiences a list has been derived of compounds of major concern due to their widespread introduction into the soil, their transportability and their persistence in groundwater in The Netherlands (Table 4). Besides the group of lower aromatic hydrocarbons and lower halogenated alkanes, -alkenes and -benzenes, oxygenated compounds such as camphor and fenchone, detected in percolate of domestic waste tips, were also found to be rather persistent.

Based on the recently obtained possibilities for assessing the exposure of organisms to groundwater contaminants, it is recommended that more attention should be given to the biological effects of these and similar chemicals.

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APPENDIX 1

Compilation of organic substances detected in contaminated ground waters in The Netherlands (concentrations in micrograms/litre)

HYDROCARBONS

Name	Highest conc.
1. Cyclohexane	30
2. C_1-Cyclohexane	1
3. C_2-Cyclohexane	1
4. C_3-Cyclohexane	3
5. C_4-Cyclohexane	0.1
6. C_6-Alkanes	10
7. C_7-Alkanes	40
8. C_8-Alkanes	10
9. C_9-Alkanes	10
10. C_{10}-Alkanes	10
11. Benzene	100
12. Toluene	300
13. Xylenes	1000
14. Ethylbenzene	300
15. C_3-benzenes	300
16. C_4-benzenes	30
17. C_5-benzenes	10
18. C_6-benzenes	0.3
19. Styrene	10
20. Limonene	10
21. Indane	10
22. Methylindane	10
23. Dimethylindane	1
24. Naphthalene	30
25. Methylnaphthalene	10
26. Acenaphthene	3
27. Biphenyl	3
28. Methylbiphenyl	0.3
29. Fluorene	0.03
30. Fluoranthene	10
31. 3,4-Benzopyrene	1
32. 3,4-Benzofluoranthene	3
33. 11,12-Benzofluoranthene	3
34. 1,12-Benzoperylene	1
35. Indenopyrene	1

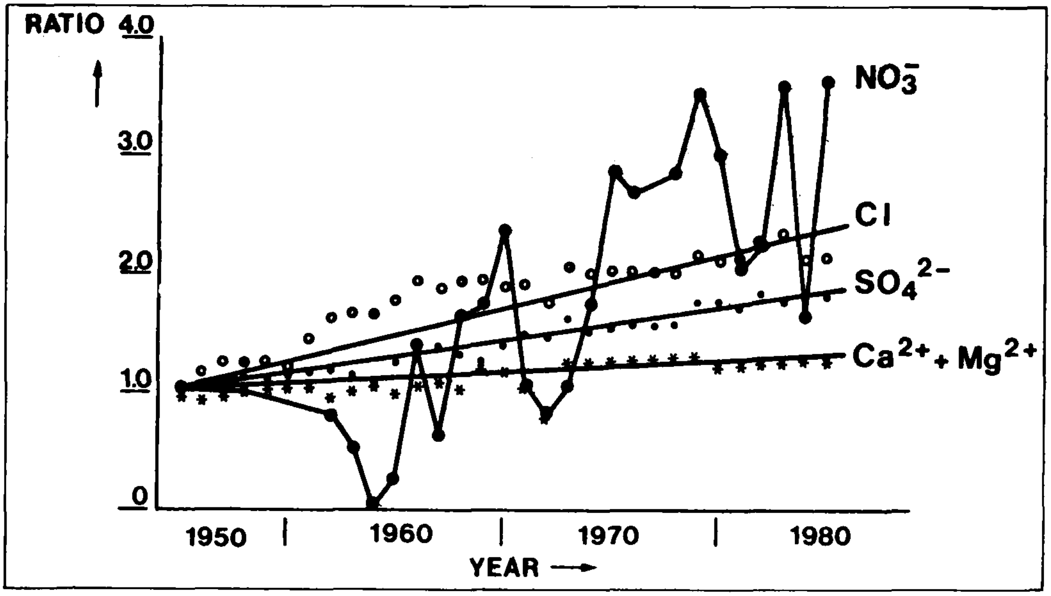
COMPOUNDS CONTAINING OXYGEN

Name	Highest conc.
36. Diethyleneglycol	3
37. Cyclohexanol	1
38. Phenolpropanol	100
39. Methylphenol	10
40. C_2-phenol	30
41. C_3-phenol	30
42. C_4-phenol	100
43. C_5-phenol	3
44. Phenylphenol	3
45. 2,4-Di-sec.butylphenol	1
46. Methylnaphtol	3
47. cis-Menthol	1
48. Dimethylbenzaldehyde	1
49. Cinnamaldehyde	0.3
50. Cyclohexanon	30
51. Di-isobutylketon	0.3
52. Octanon-3	0.3
53. Acetophenon	10
54. 1-Indanon	3
55. Conmarin	3
56. Trimethylcyclohexanon	30
57. Isophoron	10
58. Camphor	1000
59. Fenchone	100
60. Benzophenon	0.03
61. 2,6-Di-tert.Butylbenzoquinon	0.3
62. Dimedon	3
63. 1,1-Dibutoxyisobutane	10
64. Dibutylether	1
65. Dipentylether	1
66. Diphenylether	1
67. Butylacetate	1
68. Butylbenzoate	3
69. Diethylphthalate	0.3
70. Tetrahydrofuran	3
71. Dibenzofuran	0.3
72. Trimethyl-penta-diol-di-isobutyrate	1000

COMPOUNDS CONTAINING HALOGEN

Name	Highest conc.
73. Dichloromethane	3000
74. Bromochloromethane	8
75. Trichloromethane	10
76. Bromodichloromethane	0.3
77. Dibromochloromethane	0.3
78. Tribromomethane	4
79. Tetrachloromethane	30
80. 1,1-Dichloroethylene	10
81. 1,1-Dichloroethane	10
82. 1,2-Dichloroethane	3
83. 1,1,1-Trichloroethane	3000
84. Trichloroethylene	1000
85. Tribromoethylene	100
86. Tetrachloroethylene	30
87. Bromocyclohexane	10
88. Chlorobenzene	3

Name	Highest conc.	Name	Highest conc.
90. Dichlorobenzenes	3	103. 5-Methyl-,2.3-benzothiophene	30
91. Trichlorobenzenes	1	104. 4-Thiaheptane	1
92. Chlorocresols	10	105. Methylpropyldisulphide	0.1
93. 2.3.6.-Trichlorephenol	1	106. Methylisobutyldisulphide	0.1
94. 2.4.5.-Trichlorophenol	2	107. Ethylisobutyldisulphide	0.1
95. 2.3.4.-Tetrachlorophenol	3	108. Dipropyldisulphide	1
96. 2.3.5.6.-Tetrachlorophenol	5	109. Butylpropyldisulphide	0.1
97. Pentachlorophenol	1		
COMPOUNDS CONTAINING NITROGEN		MISCELLANEOUS COMPOUNDS	
98. Phenylisocyanate	10	110. Tri-ethylphosphate	0.1
99. Diphenylamine	3	111. Tri-butylphosphate	0.3
100. 2.2.4-Trimethyl-6-etoxy-quinoline	0.3	112. Tri-isobutylphosphate	10
		113. N-n-butylsulfonamide	3
COMPOUNDS CONTAINING SULPHUR			
101. 2-Hydroxybenzothiazol	30		
102. 2.3-Benzothiophene	100		



Average increase / 10 years		Average concentration 1950	1980
Total hardness	10%	16.7	21.3
Sulphate	25%	64.2	116.4
Chloride	35%	23.2	47.0
Nitrate	65%	13.8	49.8

Figure 1. Water quality changes at the pumping station Guttecoven (well's 1,2,3,5 and 8) (W.P. van der Ende, 1980)

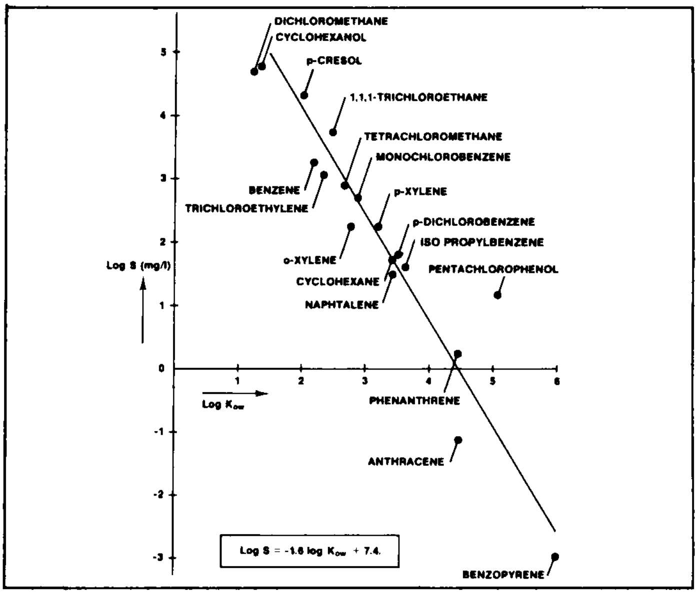


Figure 2. Relationship between log solubility and log K_{ow} of groundwater contaminants at T ∿ 20° C.

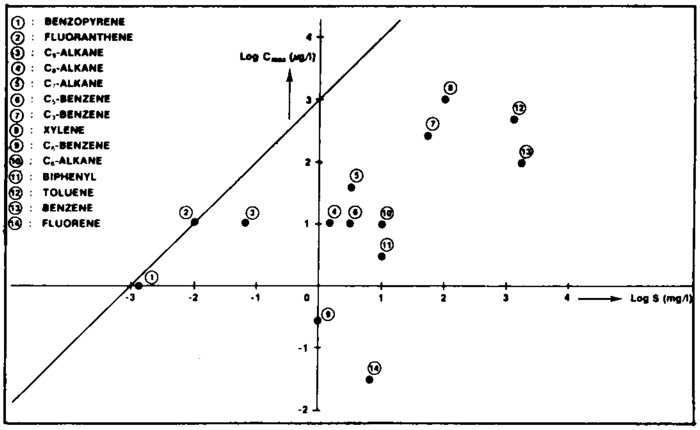


Figure 3. Highest concentrations of hydrocarbons detected in contaminated concerned groundwater and the solubility at the chemicals

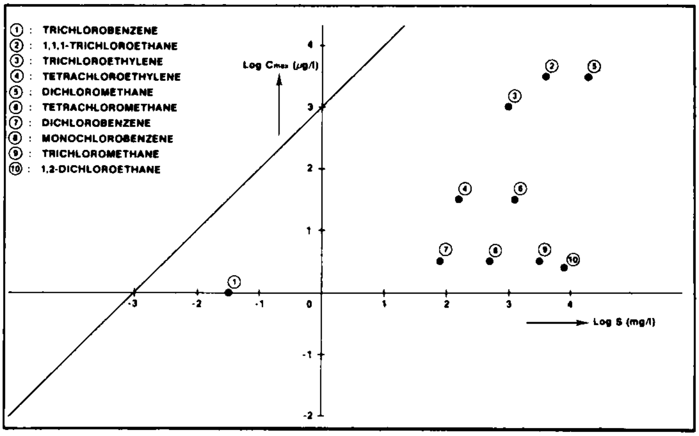


Figure 4. Highest concentrations of halogenated hydrocarbons detected in contaminated groundwater and the solubility of the chemicals concerned

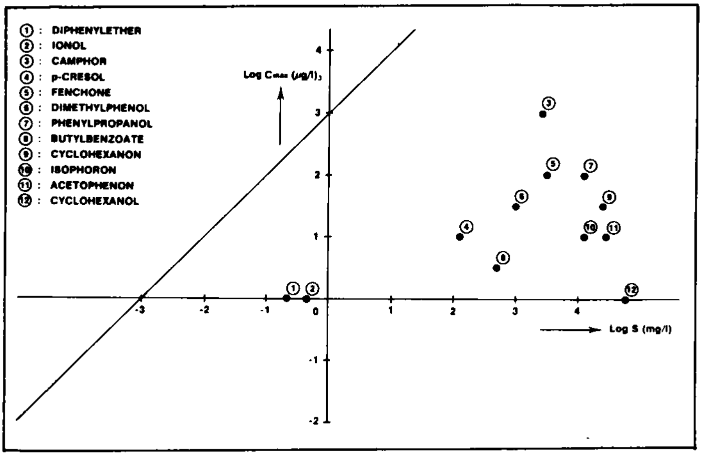


Figure 5. Highest concentrations of oxygen containing compounds detected in contaminated groundwater and the solubility of the chemicals concerned

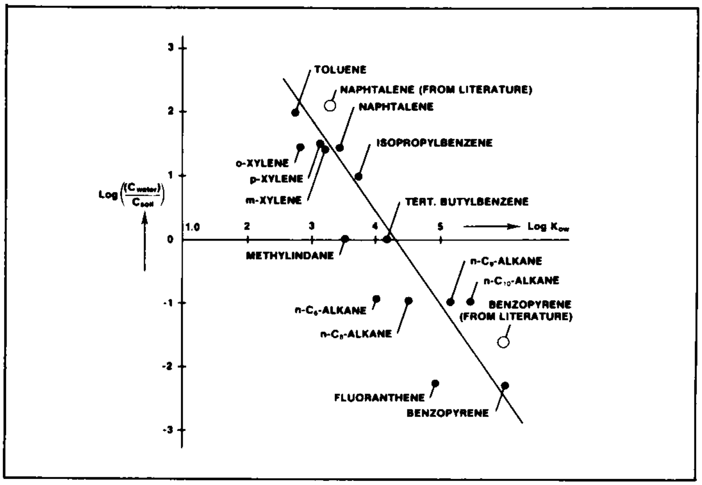


Figure 6. Relationship between the predicted C_{water}:C_{soil} ratio's and the C_w:C_s ratio's for hydrocarbons detected in Lekkerkerk and Uithoorn

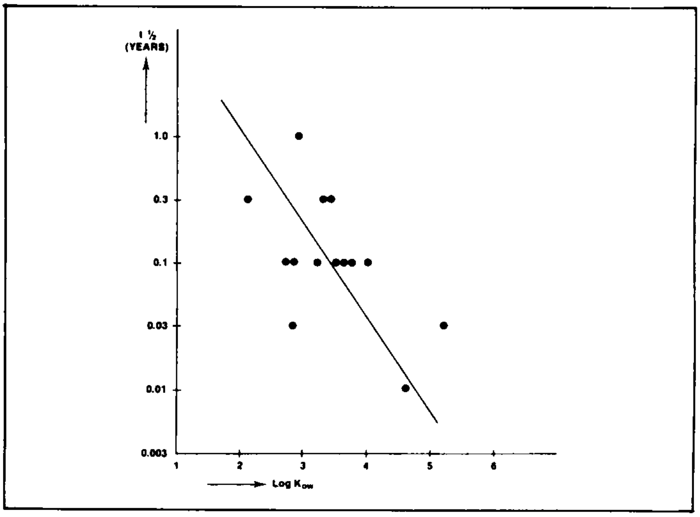


Figure 7. Half lifes of non-degradable compounds in percolate of the Noordwijk waste tip as a function of log K_{ow}